IAC-12-B4.8.12

COST-EFFECTIVE ICY BODIES EXPLORATION USING SMALL SATELLITE MISSIONS

Dr. Jonas Jonsson
SGT Inc. / NASA Ames Research Center, United States, Jonas.Jonsson@nasa.gov

David Mauro
SGT Inc. / NASA Ames Research Center, United States
Dr. Jan Stupl
SGT Inc. / NASA Ames Research Center, United States
Michael Nayak
University of California at Santa Cruz / Red Sky Research, LLC / NASA Ames Research Center, United States
Jonathan Aziz
University of Colorado at Boulder / NASA Ames Research Center, United States
Aaron Cohen
SGT Inc. / NASA Ames Research Center, United States
Anthony Colaprete
NASA Ames Research Center, United States
Andres Dono-Perez
Universities Space Research Association / NASA Ames Research Center, United States
Chad Frost
NASA Ames Research Center, United States
Benjamin Klamm
NASA Ames Research Center, United States
Julian McCafferty
NASA Ames Research Center, United States
Dr. Chris McKay
NASA Ames Research Center, United States
Derek Sears
Bay Area Environmental Research Institute / NASA Ames Research Center, United States
Michael Soulage
SGT Inc. / NASA Ames Research Center, United States
Jason Swenson
Universities Space Research Association / NASA Ames Research Center, United States
Sasha Weston
SGT Inc. / NASA Ames Research Center, United States
Fan Yang Yang
Science and Technology Corporation / NASA Ames Research Center, United States

It has long been known that Saturn's moon Enceladus is expelling water-rich plumes into space, providing passing spacecraft with a window into what is hidden underneath its frozen crust. Recent discoveries indicate that similar events could also occur on other bodies in the solar system, such as Jupiter's moon Europa and the dwarf planet Ceres in the asteroid belt. These plumes provide a possible giant leap forward in the search for organics and assessing habitability beyond Earth, stepping stones toward the long-term goal of finding extraterrestrial life. The United States Congress recently requested mission designs to Europa, to fit within a cost cap of $1B, much less than previous mission designs' estimates. Here, innovative cost-effective small spacecraft designs for the deep-space exploration of these icy worlds, using new and emerging enabling technologies, and how to explore the outer solar system on a budget below the cost horizon of a flagship mission, are investigated. Science requirements, instruments selection, rendezvous trajectories, and spacecraft designs are some topics detailed. The mission concepts revolve around a comparably small-sized and low-cost Plume Chaser spacecraft, instrumented to characterize the vapor constituents encountered on its trajectory. In the event that a plume is not encountered, an ejecta plume can be artificially created by a companion spacecraft, the Plume Maker, on the target body at a location timed with the passage of the Plume Chaser spacecraft. Especially in the case of Ceres, such a mission could be a great complimentary mission to Dawn, as well as a possible future Europa Clipper mission. The comparably small volume of the spacecraft enables a launch to GTO as a secondary payload, providing multiple launch opportunities per year. Plume Maker's design is nearly identical to the Plume Chaser, and fits within the constraints for a secondary payload launch. The cost-effectiveness of small spacecraft missions enables the exploration of multiple solar system bodies in reasonable timeframes despite budgetary constraints, with only minor adaptations. The work presented here is a summary of concepts targeting icy bodies, such as Europa and Ceres, which have been developed over the last year at NASA Ames Research Center's Mission Design Division. The platforms detailed in this work are also applicable to the cost-effective exploration of many other small icy bodies in the solar system.

I INTRODUCTION

Observations using the Hubble Space Telescope and the Herschel Space Observatory have recently indicated the existence of water vapor plumes at the Jovian moon Europa [1] and the dwarf planet Ceres in the main asteroid belt [2][3], respectively. These observations bring these worlds, together with Enceladus and its plumes, into the crosshairs in the search for habitability and the building blocks of life in the solar system. The plumes provide windows into these icy bodies' interiors, instead of needing to penetrate the thick ice crust to reach and explore the subsurface environment in-situ.

Presented here is a small satellite mission concept designed at the NASA Ames Research Center's (ARC) Mission Design Center (MDC) to the closest of these icy bodies, Ceres. The baseline is to utilizing pairs of small low-cost spacecraft. The primary spacecraft in these pairs, the *Plume Chaser*, will carry a mass spectrometer and an infrared spectrometer to characterize the vapor. Shortly after its arrival a second identical spacecraft, the *Plume Maker*, can be timed to impact with the surface in order to create a fresh ejecta plume, in case there are no natural occurrences of plume activities. This impact will be timed to coincide with a *Plume Chaser* fly-through. This enables additional subsurface chemistry, volatile content and material characterization, as well as new science complementary to that of *Dawn*.

The search for organics and the assessment of habitability form the core of the mission's objectives, making it a natural follow-on to *Dawn*. Described are the science requirements, candidate instruments, rendezvous trajectories, spacecraft design and comparison with science from the *Dawn* spacecraft.

Furthermore, the mission to Ceres can be seen as a precursor mission to a future mission to the moon Europa. This small-spacecraft, low-cost design enables the exploration of other similar solar system bodies in a reasonable timeframe despite budgetary constraints. With this in mind and using the Plume Chaser design, a mission study of this concept out to Europa was also performed. Here the differences for such a mission from that of Ceres will be discussed.

The paper starts with a background and current state of the exploration of Ceres and Europa, the science objectives and proposed instrumentation, and then continuing with the spacecraft and orbital design for a mission to Ceres. The paper then concludes with a summary of a Europa mission follow-on, and what changes to the Ceres mission would be needed.

II BACKGROUND

II.I Ceres

Ceres was long considered to be a geologically dead object in the solar system, having no gravitational interaction with any nearby objects that can fuel the activity thought to maintain the liquid ocean, such as with Europa. However, the Hubble Space Telescope detected as many as eight dark regions on Ceres, possibly craters, releasing 10^{26} molecules (~6 kg) of material per second [4]. Near-IR spectroscopy suggests that Ceres is mineralogically homogeneous [5], however, far-IR spectroscopy conducted by the Herschel Space Observatory on plumes rising from Ceres found water vapor in the vicinity of two mid-latitude dark regions, the Piazzi region (21° latitude, 123° longitude) and Region A (23° latitude, 231° longitude) [2][3]. Thermal models suggest that liquid water could exist just below the surface [6] despite a mean surface temperature of 160 ± 53 K [7]. It is likely that these regions are not craters but ruptures in the crust or even cryovolcanoes, through which water vapor and other volatiles are sublimating. Recent findings from the Dawn spacecraft detected a number of bright, highly reflective spots, whose true nature have not yet been identified, and theories range from rocks and ice or salt deposits, to volcanoes and geysers.

Ceres is also interesting from a solar system formation standpoint. It has several properties that differentiate it from planetisimals (e.g. Lutetia), fragments of larger bodies (e.g. Gaspra) and shards (e.g. Itokawa). It has a differentiated structure, with an anhydrous silicate core and water-rich mantle[6] [5][8][9]. The relatively rare CM chondrites are thought to originate from it [10] and these contain chondrules, water, and organic compounds [11]. The C-chondrite composition of Ceres is puzzling, given the basaltic crust and metallic core of Vesta, another large asteroid in the belt. One possibility is that despite containing almost half the mass of the asteroid belt, Ceres may have accreted after bodies such as Vesta; if true, it likely contains fewer radiogenic elements such as ^{26}Al. Though the Ceres origin of the C-chondrites is not certain [12], the possibility makes Ceres a high priority exploration target. Spared from the effects of the Late Heavy Bombardment (LHB) and located in a region dynamically unfavorable for planet formation, Ceres is a unique laboratory for studying the raw materials of planet formation, and linking its formation to that of the asteroids and comets.

II.II Europa

Scientists started to speculate about the possibility of a liquid ocean underneath the icy crust of Europa from images returned by the earliest flyby missions of Pioneer and Voyager. Since then further observations have revealed more details of this mysterious moon, as well as several other similar objects in our solar system that could potentially harbor liquids, and thus be habitable.

Many of the large Galilean moons can maintain subsurface liquid water environments and possibly hydrothermal-like systems. The National Research Council (NRC) rated a mission to Europa as the second highest priority flagship mission in the Planetary Science Decadal Survey *Vision and Voyages For Planetary Science in the Decade 2013-2022*, and both NASA and ESA have now set their eyes for these worlds for their next upcoming major missions: NASA's Europa Clipper and ESA's JUpiter ICy Explorer (JUICE).

Europa is believed to harbor a global saltwater ocean, containing more water than all of Earth's oceans combined underneath its frozen crust [13][14]. Estimates of the ice thickness range between 1 and 30 km [15]. It has also been suggested that the thick ice crust can be well-mixed with the underlying ocean, sufficient to transport nutrients and energy from the surface and into the ocean underneath [16]. The existence of giant shallow lakes within the ice crust has been theorized [17] and evidence of surface-shifting geological activity, i.e. plate tectonics, has been found on Europa [18]. In addition, tentative detection of potential plume activity at Europa makes a subsurface ocean more likely [19] and may indicate close proximity to the surface. These findings point Europa to being more habitable than previously thought, and thus increase the plausibility that Europa could sustain extraterrestrial life [20][16].

III SCIENCE OBJECTIVES

One of the driving questions in Planetary Science is *how life emerged in our solar system*, and *on which bodies can life or traces of life be found*. The exploration of organics, search for habitability, and characterization of the environments of our solar system form the overarching theme of the current Planetary Science Decadal Survey. This also forms the core of the Plume Chaser mission objectives, making it a natural follow-on and complementary mission to Dawn.

A summary of the science objectives for this mission to Ceres, which also extends to other similar icy bodies in the solar system, such as Europa, is listed in Table 1.

Primary Science Objectives	
A.1	Search for evidence of organics in the water vapor/plume
A.2	Determine the column water content and location of highest density
A.3	Determine the elemental composition (C, H, O, N) of any carbon rich plume particles
A.4	Characterize the particles in the plume for dissolved salts.
Secondary Science Objectives	
B.1	Characterize the silicate dust in the plume and relate it to other solar system objects, such as meteorites and comets
B.2	Characterize the mechanical, chemical and geological properties of the crust by observing the impact site before and after impact
B.3	Look for surface compositional changes on the surface associated with venting; characterize composition differences involving water or possible organics

Table 1: Summary of the science objectives of the mission, listed in order of priority. Secondary objectives source from the decadal survey, ensuring good cross-correlation with data collected by Dawn

III.I Motivation for Exploration

Along with Mars, Jupiter's icy moon Europa has long been considered a top target in the search for habitability and life elsewhere in the solar system. The 2012 Decadal Survey identified planetary habitats as a primary question: "Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?" and identified Europa exploration as an important step toward addressing said question, "The search for evidence of life is an emerging science priority for the moons of the outer solar system."

However, this search is not restricted to planets and moons, but also includes the dwarf planets and asteroids, many of which could contain the "organic ingredients for life" [21]. The recent findings from New Horizons and Dawn, the on-going missions to two of the dwarf planets in our solar system, have spurred this interest in these kinds of icy worlds. Findings have revealed that both Ceres and Pluto, although comparably small objects, seems to be more geologically active than previously thought. This was especially highlighted by the observations of the Hershel Space Observatory of possible plumes on Ceres.

Enceladus' and Europa's (possible) plumes provide windows through the icy surfaces of these bodies that present an extraordinary opportunity to sample their interiors. From the characterization of organic compounds to providing information about the objects formation, sampling the plumes will potentially answer questions about the history of biologically important molecules and contribute to our understanding of how life originated in the solar system. Information collected will also help identify the sources of the plumes, which might be ice sublimation, water evaporation from a subsurface ocean, or even volatile loss from a cryovolcano.

Compared to the other icy objects in the solar system, Ceres is a much closer target in the search for possible habitable liquid water environments beyond Earth and, in addition, Ceres can be seen as a nearby analog, and test bed, for a subsequent mission to Europa.

III.II The Plume Chaser mission concept

The *Plume Chaser* mission concept is a novel approach for low-cost exploration of the solar system. The primary objective with this spacecraft is to understand the habitability and to search for indications of life in the plumes through the investigation of their composition and chemistry. In the case that no plumes are encountered upon arrival or during the life time of the *Plume Chaser*, a sister spacecraft, the *Plume Maker* can be used to impact and artificially create ejecta plumes from the surface, ensuring that the science objectives will be met.

III.III Plume Chaser as a follow-on to Dawn

The *Dawn* spacecraft, which recently arrived at Ceres, carries a suite of instruments designed to explore the surface and the immediate subsurface. These include visible cameras for global mapping, a visible and near infrared spectrometer for mineralogy investigations, and a gamma-ray and neutron spectrometer for characterizing elemental abundances, particularly that of uranium, thorium and potassium [22]. These techniques can detect water within a meter of the surface and identify its form as hydrated minerals or water ice. Morphology and distribution of craters or pits similar to those seen on Vesta [23][24][25] will indicate the amount of water on Ceres, as well as whether the plumes originate from craters, volcanoes, or crustal rifts. Though *Dawn* has experienced issues with reaction wheels [26][27], its instruments remain proven with a successful year in orbit around Vesta [28][29]. In light of this, a relevant question to address is the added benefit that a follow-on mission to Ceres could provide.

Dawn arrived in the vicinity of Ceres when the dwarf planet was close to aphelion, while the detected outgassing event was observed at perihelion. Therefore venting can be expected to be non-existent or at its minimum during *Dawn*'s residence around Ceres [30]. It is, however, possible that *Dawn* might be able to detect intermittent vents by catching ejecta plumes on the horizon with the visible camera. If it can fly through one of these plumes after detecting it, *Dawn* might even be able to perform basic mineralogy on the ejecta using the visible and near-infrared spectrometer payload. However, the spacecraft's instrumentation is not capable of performing a precise analysis of the solid and gaseous components of the plumes. *Dawn* has no method for determining any information on the critical isotopic composition of the volatile components, which could provide insight into formation mechanisms of asteroids and comets, and the origin and history of biogenic elements. Questions such as the dust-to-water ratio of the plumes, isotopic properties of the volatiles, and resulting implications will remain unanswered. A mass spectrometer is needed to capture and detect elemental and molecular species and spectrally analyze the constituents of the plume. The *Plume Chaser* spacecraft discussed in this work will carry this important instrument.

Additionally, a controlled surface impact that can be observed will yield valuable information about Ceres' subsurface chemistry and material strength. By imaging a location before and after impact, valuable information on the nature of the crust and its mechanical, chemical and geological properties can be obtained. This is information not available from a remote sensing approach. Collection of this data has many implications for constraining observations of other, similar dark objects such as comets and C-class asteroids. Furthermore, the impact will likely trigger the release of subsurface volatiles; in the event that Ceres is not naturally venting at the time of arrival, a controlled impact would allow sampling of the interior volatiles. Complementary observation of the impact by Earth-centered observatories, such as the Herschel Space Observatory and the Hubble Space Telescope will also allow for calibrations that could aid future detections of similar events.

In addition to the significant scientific value of a follow-up mission to Ceres, there are budgetary and technology development benefits. The current exploration paradigm for planetary missions is one of multiple instruments and a budget in excess of a billion dollars [21]. The mission concept proposed here focuses on a different but complementary paradigm, dedicated to finding biologically important molecules by sending less complex and costly spacecraft to multiple destinations. For this reason, this work also details the compact spacecraft design.

III.IV Development of Mission Concepts

It is expected that more information about Ceres and the nature of its possible plume activities will be revealed as *Dawn* continues its ongoing exploration of Ceres. However, until more is known, there are three complementary possibilities that the proposed concept must be capable of performing within. Each of these scenarios are described further below.

III.IV.I Venting from the surface is common.

In the scenario where venting from the surface is common, an exosphere with a varying but detectable density of molecules from beneath the surface can be expected. The spacecraft must be able to sample this tenuous exosphere, task referred to as the “sniff” operation. For this scenario the *Plume Chaser* spacecraft must enter into low circular orbit and sample the exosphere using the mass and infrared spectrometers. In this scenario the addition of the *Plume Maker* induced impact ejecta might not be critical to meet the science objectives, however, the impact would also provide with a freshly excavated surface for remote investigations.

III.IV.II Venting uncommon, but occasional.

It is believed that the venting events on Ceres could be periodical, occurring primarily at perihelion. In this case the trajectory must be designed to establish orbit around Ceres prior to any expected outbursts at perihelion, approximately two to three months. Given this condition, the spacecraft will likely encounter one or more plumes. The lifetime of vented molecules in the exosphere is expected to be short and therefore the spacecraft needs to be capable of lingering in orbit until a plume is detected, after which it can be maneuvered to sample it. We refer to this task as the “wait” operation.

The data would be collected on the ramp-up of plume emissions and consistently revisited until approximately one to two months after perihelion. An impact by *Plume Maker* would be timed to follow this collection period, as to not interfere with the naturally occurring venting events.

III.IV.III Venting is rare or non-existent

The case could also be that the venting is rare, or even that the plumes detected by Herschel Space Observatory were a sporadic occurrence under extremely favourable conditions. A trace exosphere or residue from prior out-gassing may be beyond the detection limit of the instruments, and it is possible that no additional sublimation or eruptions could appear during residence around Ceres. In this scenario, the addition of Plume Maker will help guarantee scientific return. The impacting spacecraft should arrive after the initial completion of the wait and sniff tasks, as to not disrupt studies of any natural plume activities, before artificially creating the plume and eject volatile material for Plume Chaser to fly through. This task of coordinated impact and plume sampling is referred to as the “impact” task. Following impact observations, the orbiter returns to the wait and sniff tasks before departing the target body before the end of life (EOL).

III.IV.IV Plume Maker Observation Window

In the scenarios above, when *Plume Maker* impacts the surface and creates the artificial plume, *Plume Chaser* will fly through the ejecta, enabling the subsurface science characterization goals of the mission even in the case there are no naturally occurring plume events. In order to fulfill the science objectives, determining the post-impact observation window is an important factor to enable this return. Considering predicted impact characteristics, distributions of ejected particles versus time after impact were simulated [31][32], where the orbital altitude of 200 km is of interest, Fig. 1.

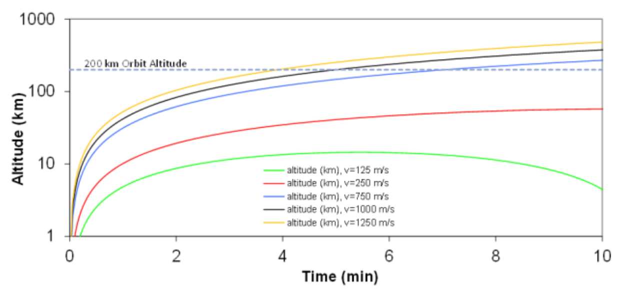

Fig. 1: Altitude versus time after impact: Distribution of ejected particle velocities. Velocities are with reference to the Ceres surface.

According to these results, if *Plume Chaser* arrives less than two minutes after impact an adequate number of particles may not have reached the observation altitude. Further, particles with a velocity of over 500 m/s will not reach the 200 km altitude. Even when combined with a component of the spacecraft's velocity, these particles are at the edge of a miniaturized spectrometer's minimum required ionization speed. Therefore the collection and analysis of particles were focused on for the 750 to 2000 m/s range. It can be observed that a majority of these particles have crossed the 200 km observation altitude after a post-impact time of six minutes. In this case, the window for *Plume Chaser* to reach at the impact site with a targeted number of suitable particles at its orbital altitude of 200 km is between 2 to 6 minutes after impact.

III.V Instrumentation

To fulfill the science objectives, a payload of three-instruments is proposed: a mass spectrometer, an infrared spectrometer, and a visual/infrared camera. The science traceability matrix, presented in Table 2, demonstrates how tentatively proposed candidate instruments might fulfill science objectives. In addition to the science return of these instruments, responses from the three-axis stabilized attitude determination and control system (ADCS) can provide measurements of column density as it flies through the plume.

Science Objectives	Capable Instruments	Instrument Functional Requirements	Mission Functional Requirements
A.1 Search for evidence of organics in the water vapor/plume	ENIJA IR spectrometer	Physical capture and detection of elemental and molecular compounds	Fly through plume at closest approach
A.2 Determine the column water content and location of highest density	ENIJA IR spectrometer NanoCam C1U S/C ADCS	• Same as A.1 • Spectral analysis of H2O emission lines at 1.89, 2, 2.7 and 3 um wavelengths • Characterize disturbance torque on spacecraft during flyby	Align instruments with velocity vector Collect up to 40 seconds of data from instruments
A.3 Determine the elemental composition (C, H, O, N) of any carbon rich plume particles	ENJIA IR spectrometer	Collect and compositionally analyze between 10 nm and 100 um sized particles with mass spectra in the 1 – 2000 amu range	
A.4 Characterize the particles in the plume for dissolved salts.	ENIJA IR spectrometer	Same as A.3	
B.1 Characterize the silicate dust in the plume and relate it to other solar system objects, such as meteorites and comets	ENIJA IR spectrometer	Same as A.1	No additional requirements
B.2 Characterize the mechanical, chemical and geological properties of the crust by observing the impact site before and after impact	NanoCam C1U IR spectrometer	• 400 – 1000 nm spectrum • 35 mm / f1.9 lens, 9.22 deg field-ov-view (FOV) • Resolution of < 80 m per pixel	Point spacecraft camera at surface before and/or after flyby
B.3 Look for surface compositional changes on the surface associated with venting; characterize composition differences involving water or possible organics	IR spectrometer	Spectral analysis of H2O emission lines at 1.89, 2, 2.7, and 3 um wavelengths	No additional requirements

Table 2: Science traceability matrix

All three of *Plume Chaser*'s instruments will be located on the face opposite the propulsion system, allowing for the capture of imagery and particles as the spacecraft flies through the plume. The approach trajectory must keep the sun behind the spacecraft to allow collection of spectral and visible backscatter from the plume. After passing through, the spacecraft can rotate toward the anti-velocity vector to observe the sun and collect transmission spectra. Simultaneous camera observations in backward and forward scatter will constrain grain sizes and concentrations. During additional orbits, the spectrometer and camera can record spectral surface characteristics and high-resolution images that can complement and constrain other observations, and help characterize potential future landing sites on the targeted body.

III.V.I Mass Spectrometer

To fulfill the science requirements and maximize instrument return, a mass spectrometer optimized for high impact rates and a gas and plasma-rich background is desired. This instrument should be able to collect and analyze 10 nm to 100 µm sized particles with mass spectra in the 1 to 2000 atomic mass units (amu) range. This makes it sensitive to water ice, minerals, metals, organic particles and mixtures of these components, optimal for detecting biologically important molecules. This wide range also permits characterization of the particle chemistry of individual ions like H+, C- and O-, as well as complex organics with heavier atomic masses.

An example of a suitable instrument is the Enceladus Icy Jets Analyzer (ENIJA), a reflection-based impact-ionization time-of-flight mass spectrometer developed by the University of Stuttgart for the detection of individual hypervelocity dust particulate impacts [33]. Developed through miniaturization of flight-proven hardware from *Cassini* and *Stardust*, with a TRL of 4, the instrument has measurement modes for either cations or anions formed upon impact and can simultaneously determine the mass of detected grains. Further, it can capture and detect elemental and molecular species that might indicate a salty ocean source for the water vapor, including Na, H_2O, H, C, O, $(H_2O)nNa+$, $(NaOH)nNa+$, $(NaCl)nNa+$ and $(Na_2CO_3)nNa+$ [34].

An important consideration for miniaturized spectrometers is the ionization speed. Collections by the spectrometer are produced by high-velocity impacts of individual particulate grains onto a metal target. To be ionized and measured, molecules must impact the detector at speeds typically in excess of 1 km/s. However, a stable repeating orbit for science collection around Ceres will give *Plume Chaser* an orbital velocity in the 0.2-0.3 km/s range; in fact, the maximum achievable velocity from Ceres orbit is the escape velocity of 0.53 km/s. For this scenario, the natural ejection velocity of particles from the impact event can be leveraged for ionization. This velocity has been measured at 0.3-0.7 km/s; particles on ballistic trajectories are ejected with velocities exceeding 1 km/s [3]. If the miniaturized spectrometer is mounted on the nadir-facing surface at a 45° angle, combined with the velocity of the spacecraft, a large number of particles will impact the spectrometer with sufficient velocity for ionization at a measurement altitude of 200 km.

III.V.II Infrared Spectrometer

Good detection sensitivity for C-H and N-H bonds, which are indicative of hydrocarbons and other organics, is strongly desired for the mission's infrared spectrometer. A primary science objective of the *Plume Chaser* mission is the detection and determination of the location of greatest plume density; this is possible by imaging H_2O emission lines at 1.89, 2, 2.7 and 3 µm wavelengths. Therefore the optical range must be at least 1.8 to 3 µm. The selected spectrometer should also be capable of measuring particle scattering in both emission and absorption modes, depending on the viewing angle, to yield more size and shape information on the ejected particles.

An example of a capable instrument is an infrared spectrometer being jointly developed by NASA Ames Research Center, Draper Laboratories and ThermoFisher Scientific. Currently at a TRL of 6, this single-aperture spectrometer has dimensions of 0.8U for optics and 1U[*] for electronics. The instrument has an optical range of 1.6 to 3.4 µm and 0.15 µm resolution. This spectral band is sensitive to water in both gas and solid phases. The 1.89 and 2 µm bands are twice as sensitive as the shorter 1.38 to 1.5 µm bands, and the 2.7 and 3.0 µm bands are fifty times more sensitive. Further, the edge of the detection range, at 3.4 µm, allows good detection sensitivity for C-H and N-H bonds.

III.V.III Visible Wavelength Camera

During spacecraft approach, autonomous software that uses visual-based navigation techniques [35][36][37] will be used for guidance into orbit, and subsequently toward plumes of interest. In addition to being part of the payload, the visible wavelength camera is therefore an integral part of the Guidance, Navigation and Control (GN&C) subsystem. Results from camera imagery taken concurrently with plume infrared spectroscopy will improve guidance during subsequent passes, enabling the spacecraft to intersect the plume.

To allow plume imagery, a camera with a visible and near-infrared detection range is required. An

---

[*] 1U denotes a volume of 1 liter, according to the CubeSat standard.

example of a candidate instrument is the GomSpace NanoCam C1U visible wavelength camera, developed specifically for CubeSats. It is currently at a mature TRL of 9, though additional testing will be needed for radiation shielding and applications beyond Low Earth Orbit (LEO). Its 3 MP CMOS sensor has 10-bit color and a 400 to 1,000 nm capture spectrum. A 35 mm / *f*1.9 lens gives the camera a 9.22° field-of-view (FOV) and a resolution of less than 80 m per pixel from an orbital altitude of 650 km [38], enabling it to fulfill all desired objectives.

IV SPACECRAFT DESIGN

To fulfill all the science requirements, a two-spacecraft architecture with one orbiter and one impactor, named *Plume Chaser* and *Plume Maker*, respectively, is proposed. Both *Plume Chaser* and *Plume Maker* fall into the microsatellite category, having a wet mass of less than 190 kg. To meet the challenges of a low-cost small-spacecraft mission, *Plume Chaser* is designed to fit within the ESPA Grande volume envelope [39] and is compatible with a 61 inch height Moog Engineering ESPA Grande ring adapter [40].

The spacecraft have the dimensions of 40 cm x 40 cm x 30 cm. One of the main challenges associated with the spacecraft concept is to keep the dry mass as low as possible while maintaining the structural integrity and a proper radiation shielding of the spacecraft. The vehicle model concept is composed of a main avionic and payload module located in its center and a propulsion module, which wraps around the avionics payload module. The solution implemented uses a 3D printed titanium tank for propellant storage and radiation shielding. This dramatically reduces the mass of the structure and shielding required for the mission. Also, another benefit of this design architecture is to add modularity by having two independent modules, propulsion and avionics, which facilitates implementation, assembly and testing.

Plume Maker's avionics package, propellant tank and fuel mass are identical to that of *Plume Chaser*, though removal of the payload package reduces the dry mass and allows for additional propellant that can be used to increase the impact velocity. Fig. 2 shows the baseline design.

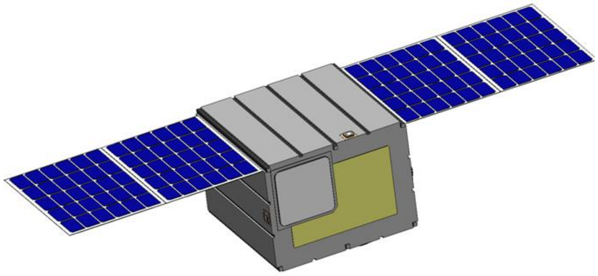

Fig. 2: Baseline designs for the *Plume Chaser* and *Plume Maker* spacecraft.

Following subsections gives further details on selected subsystems of the spacecraft design, such as the CubeSat Ambipolar Thruster (CAT) engine.

IV.I Propulsion

The selected propulsion system for the *Plume Chaser* and *Plume Maker* spacecraft is the CAT engine [46], under development at the University of Michigan, Fig. 3. Plans are for it to be spaceflight tested in 2015, which will raise this system's TRL to 8 [47]. This design consists of a radio antenna that launches a helicon wave and turns the iodine propellant into plasma. The wave heats the electrons that transfer their thermal energy into ion kinetic energy via an ambipolar electric field. Electrons and ions are ejected through a magnetic nozzle to produce thrust. The propellant is stored in tanks and is injected into a plasma liner that consists of a quartz chamber that tolerates high temperatures and directs the flow of gas. Then, the plasma is accelerated out of the liner with magnetic fields that are generated from powerful permanent magnets. A 3D printed faraday shield made of titanium encloses the thruster and the antenna while acting as a support for both the liner and magnets.

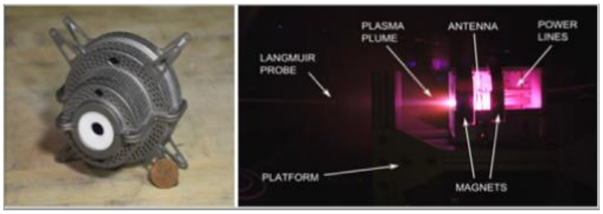

Fig. 3: CubeSat Ambipolar Thruster (CAT) engine.

This technology presents a breakthrough in the current capabilities of propulsion systems for small satellites. The propulsion system fits in a 1U CubeSat form factor and the propellant tanks accommodate 25 kg of iodine propellant for every 5U of volume. With this configuration, a small volume can satisfy a high delta-V requirement and gives greater flexibility for a variety of missions. Multiple propellants can be used, although iodine is selected for this mission due to its high efficiency of over 60 percent, depending on the power and the specific impulse, and high molecular density of 5 g/cm^3. The power required for operation ranges from 3 to 300 W and has been previously demonstrated. The total power allocated for the propulsion system is 175 W. This configuration optimizes the mass budget for the propulsion system and complies with the operational thruster power requirements. The propellant tanks are blended into the design of the spacecraft, being part of the structure, and 3D printed. Details on the plasma acceleration mechanisms within the engine are in the literature [48].

IV.II Power

Plume Chaser has power requirements unique to a microsatellite; it must be able to sustain high average power dissipation at an increasing distance from the sun. The CAT engine is able to use 175 W of power and can be fired for days or weeks at a time.

For a distance of the Ceres orbit, of about 3 AU, solar arrays sized to the minimum solar intensity of the targeted body were found to be able to provide sufficient power. The solar intensity comes out to 11.27% of that at Earth (154 W/m^2). This results in an active solar panel area of 0.72 m^2 and solar array mass of 2.5 kg without a gimbaled system. At Ceres, the CAT engine will no longer need to provide maximum thrust. For the electrical power system (EPS), a proven design with flight heritage is strongly preferred. In-house designs by NASA Ames can be tailored to the specific requirements of the mission. The design is aimed at reuse of the heritage of the nanosat bus flown on GeneSat [41], PharmaSat [42], Nanosail-D2 [43], O/OREOS [44], and SporeSat [45], and subsequently advances these designs to satisfy the demands of a propulsion system.

IV.III Attitude Determination and Control System (ADCS)

ADCS requirements are derived from performance data of previous interplanetary spacecraft that performed gravity-assist flyby maneuvers. Pointing requirements for the Cassini spacecraft during the Enceladus-5 flyby are used as a baseline to size the *Plume Chaser* ADCS [49]. The estimated worst-case external disturbance torque when flying through a plume was approximately 125 mN·m at Enceladus [50], well below *Plume Chaser*'s maximum angular momentum storage of 500 mN·m per axis. In the Saturn system, Cassini required a pointing accuracy of over, or equal to, 0.34° for flyby maneuvers.

Candidate systems to fulfill these requirements include the RWp-500 reaction wheels from Blue Canyon Technologies and an accompanying nano-star tracker [51][52]. For reaction wheel de-saturation, candidate ADCS systems include the Busek µPPT-1 Micro Propellant Attitude Control System (MPACS) cluster [53], which hosts pulsed plasma thrusters with flight heritage from FalconSat-3 [54]. Coupled with nanosatellite specific models to manage disturbance torques [55], the spacecraft will be capable of meeting all objectives.

IV.IV Telecommunications

Technical challenges arise with regard to the feasibility of telecommunications for a small satellite at Ceres. By extrapolating assumptions from analysis of telecommunications with CubeSats in the Martian system [56] and assuming the use of two-arrayed 34-meter Deep Space Network (DSN) dishes and the Opportunistic Multiple Antenna per spacecraft scenario [57][58], we conclude that communication to Ceres orbit is feasible with an onboard antenna capable of transmitting at 20 dBi gain. However, most CubeSat systems at a TRL of 9 use simple low gain antennas (max 6 dBi) and operate in the UHF or S-Band with no navigation capability.

Recent developments point in the right direction, such as the DSN compatible X-band Iris CubeSat transponder [59]. Alternately, multiple antenna solutions could meet mission needs; a patch antenna array capable of 20 dBi gain with a mass at, or under, 0.5 kg can close the link at Ceres range. Inflatable antennas being developed at the Jet Propulsion Laboratory (JPL) offer a promising 30 dB gain with a 2 m parabolic dish for a stowed volume to fit inside a 2U volume and a total mass of less than 2 kg [60]. Therefore, there are multiple candidate solutions to close a link budget for the proposed mission.

V ORBITAL DESIGN

Both the Plume Chaser and the Plume Maker will use electric propulsion and will be launched as auxiliary payloads into a Geosynchronous Transfer Orbit (GTO). Separating from a launch vehicle on its way to GEO is an opportunity for total fuel, e.g. delta-V, and time-of-flight (TOF) savings, and thus reducing the cost of the overall mission. Sharing a launch into this orbit has become increasingly cost-effective in recent years and it is expected to be even more optimal in the upcoming future due to the increment in GTO launches. In 2013, more than six launches into this orbit were performed from Kennedy Space Center. In addition, commercial space companies such as SpaceX have increased their frequency of launches per year. For 2014, at least four GTO launches are scheduled with the Falcon 9 rocket [61].

Since *Plume Chaser* and *Plume Maker* fall into the microsatellite category, they may be mounted either vertically or cantilevered, increasing the number of launch opportunities as a secondary payload.

Another potential implementation for the mission scenario is to use the spacecraft as a piggyback aboard an interplanetary rocket. An interplanetary launch would provide a positive characteristic energy that would push the spacecraft outside the Earth's sphere of influence and significantly decrease the delta-V budget, propellant mass and time-of-flight (TOF).

The idea with this mission concept is to set a baseline for an accessible and easy exploration of the solar system. Standardization is needed for this ambitious goal and the same approach can be potentially used for many other mission concepts. Hopefully, this scenario can help to pave the way for low-cost interplanetary exploration.

As discussed above, *Plume Chaser* targets an arrival into a 200 km science orbit around Ceres between 1 to 4 months prior to the July 2027 Ceres perihelion. Other trajectory constraints include the use of solar electric propulsion, a maximum TOF of 5 years, an initial wet mass of between 140-200 kg and at least 50 W of power available to the spacecraft bus at any time during the trajectory. A propellant-power trade study found a relatively suitable window in January 2022 that meets these constraints.

For a departure epoch of 1 Dec 2021 with an initial wet mass of 170 kg and initial power of 1 kW, the baseline trajectory, Fig. 4, delivers 53 kg of mass to Ceres in 4.8 years, on 31 Mar 2027. After orbit insertion, 2.36 km/s of delta-V is available for science and EOL operations. Due to the low gravity, station keeping consumes minimal fuel, leaving a 43 kg dry mass and 1.75 km/s of delta-V at the end of the 12-month nominal mission lifespan, enough to enable an extended mission.

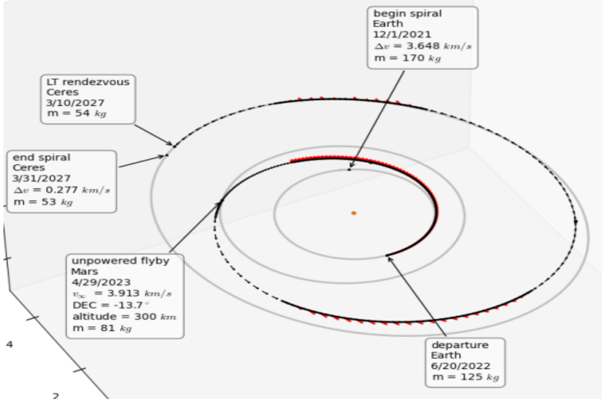

Fig. 4: Interplanetary trajectory for *Plume Chaser*.

The *Plume Chaser* trajectory utilizes a Mars Gravity Assist (MGA) to reach Ceres. Since most of the plume activity is centered on the mid-latitudes [2][3], the target science orbit has an inclination of 21-25° to allow for maximum dwell time over these regions. Observations from *Dawn* will hopefully help narrow the focus of future design iterations. Fuel is held in reserve to execute a hyperbolic escape trajectory at the conclusion of the mission. EOL will occur on this path, designed such that it will not intersect a planetary body for at least 50 years.

Plume Maker's trajectory design faces different challenges. This spacecraft must arrive at Ceres with sufficient mass and velocity to excavate a crater no less than 10 m wide and 3 m deep. Fig 5 presents the crater depth-diameter curves for a 40 kg impactor with an impact velocity of 10 km/s. The impact angle bounds the trade space for the design of the trajectory from Earth.

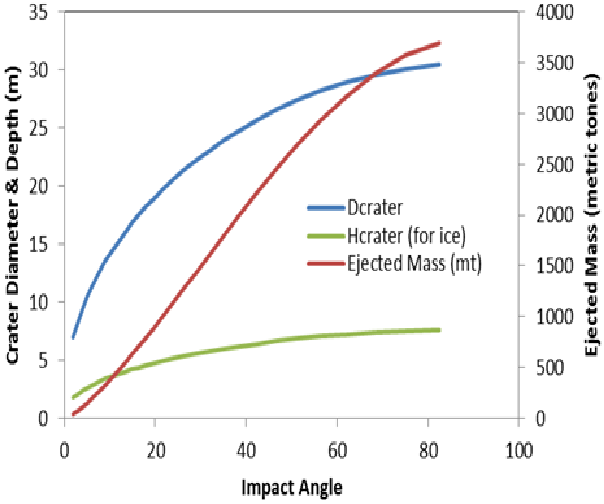

Fig. 5: Depth-diameter curves vs. impact angle for an impact velocity of 10 km/s. Diameter of the crater (Dcrater, blue line), depth of the crater for an icy surface (Hcrater, green line), and ejected mass in megatons (red line), are shown.

Similar requirements of 50 W of power to the bus at all times and a maximum TOF of 5 years are levied, with the additional constraint to arrive 3-5 months after the July 2027 perihelion. This allows *Plume Chaser* time to conduct the sniff and wait mission sets; a thorough operational understanding of the spacecraft during this time will help ensure rendezvous within the two to six minute post-impact observation window. Additionally, for possible future planetary protection considerations, a hypervelocity impact should be able to vaporize the impactor [62]. A lower limit of 3 km/s has been proposed to fulfill this requirement [63][64]; therefore *Plume Maker* must arrive at Ceres with at least this velocity in the local frame.

A trajectory trade study was performed seeking to maximize impact energy and minimize time of flight. Assuming a co-manifested launch with *Plume Chaser* for cost reasons, *Plume Maker* will remain in GTO until departure on a direct intersection path with Ceres. However, since it is possible that a launch opportunity closer to the departure date may be attainable; this pre-Phase A analysis does not consider GTO station-keeping costs. For a GTO departure epoch of 21 May 2025 with an initial wet mass of 140 kg and initial power of 1 kW, the baseline trajectory delivers 41 kg of impact mass to Ceres in 2.1 years, with an impact date of 26 Nov 2027, Fig 6. As designed, this trajectory creates an impact velocity of 9.3 km/s, generating impact energy of 1.76 GJ.

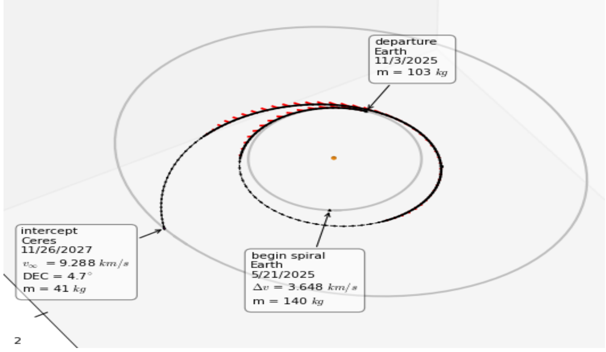

Fig. 6: Interplanetary trajectory for *Plume Maker*.

It has been proposed that the ice on Ceres may be unstable on the surface and down to a depth of a few tens of meters below a regolith layer [8]. The baseline impact trajectory is very likely to exceed the minimum required crater and excavate material from beneath regolith tens of meters deep. However, if greater velocities are deemed necessary, the trajectory design space does include the potential for impact energies as high as 2.75 GJ and velocities up to 11.1 km/s.

VI EUROPA MISSION FOLLOW-ON

The Plume Chaser spacecraft can be adapted for a follow on mission to the icy bodies further out in the solar system. A follow-on mission to Jupiter's moon Europa was designed. Much of the mission and spacecraft design from the Ceres mission above can be reused here, but a number of changes are needed, especially for the orbital design, radiation and planetary protection considerations, as well as the power and thermal management subsystems.

VI.I Orbital Design

The Europa Plume Chaser mission concept considers two scenarios that differ a bit from that of the Ceres Plume Chaser spacecraft with the impacting Plume Maker spacecraft. The two scenarios are referred to as the *Europa Direct Flyby* and the *Jupiter Capture Flyby*. In the first scenario, two or more spacecraft travel directly to Europa for a single flyby from a highly elliptical heliocentric orbit. In the second scenario, a single spacecraft will go into orbit around Jupiter and perform three close passes of Europa. To achieve the scientific objective in both of these scenarios, the spacecraft will make close flyby to Europa's surface in order to characterize any plumes being ejected.

VI.I.I Europa Direct Flyby

The Europa Direct Flyby scenario consists of at least two Plume Chaser spacecraft flying in a highly elliptical heliocentric trajectory to Europa. Both spacecraft will perform flybys of Europa, where the first will detect the plume to locate the densest portion, while the following spacecraft will travel through the plume to perform the science measurements. The spacecraft flying through the plume will be 3-axis stabilized with the instruments pointing in the direction of the satellite motion, i.e. ram direction. After the flight through the plume, the spacecraft will turn to the opposite direction to observe the sun through the plume in order to capture transmission spectra.

This Direct Flyby scenario considers two stages in the trajectory analysis. First the spacecraft goes from a GTO to the end of Earth's SOI. In order to escape Earth's gravity, the spacecraft performs a lunar gravity assist. At the second stage, the spacecraft is propelled to go directly to Europa in an elliptical heliocentric trajectory and performs a hyperbolic flyby, Fig. 7. The total time-of-flight for this case is 7.7 years while the delta-V requirement is 13.9 km/s. Both spacecraft will pass Europa at an altitude of 25 km with a closing velocity of 5.6 km/s.

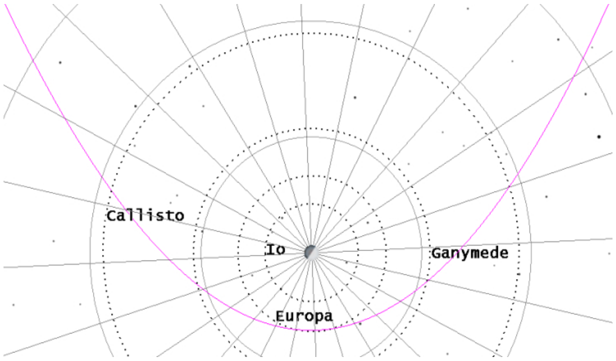

Fig. 7: Hyperbolic trajectory to Europa.

After its fly-by, the spacecraft will continue on the hyperbolic Jovian trajectory beyond the SOI. Some margin of propellant mass will remain, providing a residual delta-V of ~2 km/s that enables an extended mission. One option then is to escape the Jovian system and target another planetary system. The Saturn system and beyond will require leveraging gravity assists. Another possible option uses the excess delta-V for insertion into a highly elliptical orbit to further study of the Jovian moons. This mission extension maximizes the science return and sets the basis for accessible and sustainable exploration of the interplanetary environment.

VI.I.II Jupiter Capture Flyby

The Jupiter Capture Flyby scenario consists of a spacecraft that will enter a highly elliptical orbit around Jupiter and perform three passes over Europa's surface. In the first flyby, the spacecraft will locate and observe any plume activity and fly through it during the second pass. Similar to the first scenario, the spacecraft flying through the plume will be 3-axis stabilized with the instruments pointing in the ram direction. Once it has gone through the plume, the spacecraft will rotate 180 degrees to observe the Sun through the plume in order to capture transmission spectra.

The interplanetary trajectory is designed using the patched conic method and is divided into four different legs. The first leg starts at the GTO orbit when the electric thrusters turn on and propel the spacecraft out of the Earth's SOI, using lunar gravity assist. The second leg begins when the spacecraft escapes Earth's gravity and performs a heliocentric spiral orbit around the Sun to reach Jupiter's SOI. During the third leg, the spacecraft is injected from Jupiter's SOI into the science orbit around Jupiter, Fig. 8. The last leg, or decommissioning phase, will place the spacecraft into a collision trajectory with Jupiter. The overall duration of the mission is 10.2 years and it requires a total propellant mass of 141 kg to provide a total delta-V of 17.8 km/s to place a dry mass of 40 kg from Earth's GTO into a science orbit around Jupiter and decommission in the Jovian system.

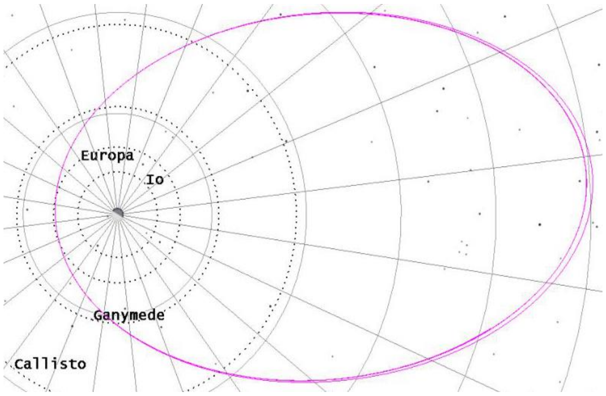

Fig. 8: Jupiter Capture Flyby orbit.

VI.II Power

While a deployable solar panel could provide power for an earth-departure burn, and even for a Ceres insertion burn, it would be difficult to sustain such power dissipation at Jovian distances. The average solar intensity of the Jovian system is 49.7 W/m^2, or about 3.7% of the solar intensity at the Earth's orbit. This means that a deployable solar panel that generates 175 W at Earth's orbit would only generate 6.5 W in the Jovian system.

In order to operate the ion propulsion system in the outer solar system, an alternative power source is required. The technique focused on here is radioisotope thermophotovoltaic (RTPV) power source developed and provided by Idaho National Labs (INL). An RTPV generates power from a radioisotope covered in tungsten cement. The radioactive decay heats the tungsten cement to incandescence; the emitted photons are then absorbed by photovoltaic cells. An RTPV system that generates 227 W of power at beginning of life (BOL) would contain 2 kg of PuO2, with an overall system mass of 5.5 kg, and occupy a volume of 940 cm^3. With a predicted thermal efficiency of 28%, the thermal dissipation would be 567 W. Estimated end of life (EOL) power after an eight-year mission, such as in the case for Europa, would be 200 W. The spacecraft design from the Ceres mission is modified to accommodate this power subsystem, Fig 9.

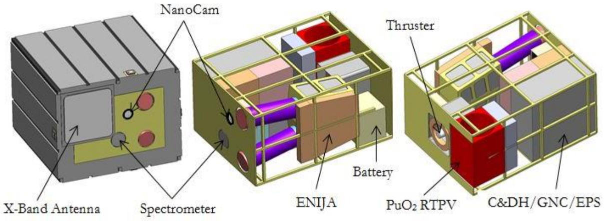

Fig. 9: RTPV designs for the *Plume Chaser* and *Plume Maker* spacecraft.

VI.III Thermal

The thermal design uses a fully passive system utilizing deployed radiators to control component temperatures, which avoids additional active cooling/heating system power losses. It should be noted that most of the heat required for dissipation comes from the PuO2 RTPV power supply, which generates 567 W of waste heat at mission start. Also, the orientation and position of the spacecraft is paramount, since it will determine the heat dissipation rate due to the placement of the RTPV and deployed radiator panels.

The key thermal requirements are:

1) to maintain the propellant below 60° C,
2) to maintain the different subsystems within their thermal operating range,
3) to maintain the RTPV photovoltaic cells at 70° C, plus or minus 10° C, to maintain operating efficiency, and
4) to maintain a <10° C temperature gradient within the iodine fuel feed system running between the tank and CAT engine, to avoid condensation.

In order to fulfill the above requirements two thermal mission phases must be considered: launch vehicle integration lifetime and post launch vehicle separation. During launch vehicle integration, the spacecraft and deployer rack will be actively cooled using an ablative solid-nitrogen system. After launch vehicle separation, the radiating panels will be automatically deployed and lock into position for the duration of the mission. The thermal conductance path between the power source and the spacecraft will be designed to thermally integrate the RTPV heat into the vehicle skin and radiator panels.

The following key assumptions are made:

- both large spacecraft faces are used for radiating energy (40x40 cm faces),

- IR emissivity is assumed to be 0.88 (consistent with silvered Teflon, 0.25 mm thick),
- the RTPV dissipates 567 W thermal,
- the target uniform steady-state satellite skin temperature is approximately 50° C,
- the solar flux is neglected for this calculation (its contribution is much less than the 567 W generated by the RTPV).

After taking the above into account, to satisfy the energy balance, 0.63 m^2 of additional radiator area is required. With the two 40x40 cm radiator panels (sized to match the area of the top and bottom surfaces) fully deployed and assuming they radiate with a 0.88 emissivity equally from both the front and back surfaces, the thermal energy dissipated is slightly more than required to maintain a 50° C skin temperature.

VI.IV Radiation protection

Radiation protection is of major concern for a Europa mission, where, in addition to the radiation received during the long interplanetary travel, the environment around Europa is subjected to the strong radiation driven by Jupiter's magnetic field. Plume Chaser must endure between a three to eight year interplanetary transit depending on scenario, which starts from a geosynchronous transfer orbit and finishing in either single or multiple Europa flybys, which pass through the densest portion of the Jovian trapped radiation environment. A four-part methodology is used for both scenarios to meet commonly accepted radiation susceptibility requirements for use of various COTS electronics components, applied in the following order:

1) a standard chassis shielding mass assumption (which in this case includes the titanium propellant tank as a majority of the chassis),
2) sector shielding due to inherent spacecraft mass,
3) spot shielding, and
4) radiation-hardened component up-selection.

The sector shielding analysis determines the dosage gradient within the spacecraft, and critical components are then placed in a more centralized spacecraft location if possible. If the sector analysis returns a dosage above threshold requirements for specific components and relocation is not feasible, spot shielding is then applied directly to said component in a sufficient amount to meet dosage requirements.

VI.V Planetary protection

Also the issue of planetary protection is mostly applicable to Europa, since Ceres has a low planetary protection category. However, this is subject for review depending on the results found on future discoveries. This is particularly true if it will be found that Ceres does harbor liquid water, where a classification similar to Europa can be expected.

The planetary protection requirement for a Europa mission, in line with current recommendations [65][66], maintains a less than 1/10,000 chance that a viable organism will be introduced into Europa. Taking into account the characteristics of the herein proposed mission concepts, they should both be classified in a Planetary Protection Category III, since they will be performing flybys of Europa. However, due to the sensitivity of the mission and the possibility of an impacting encounter with Europa, a more thorough sterilization process, similar to the Viking landers, should be taken into consideration. This could include reducing the bioburden, i.e. the number of carried living microbes, to Category IVa, followed by heat treatment at 125 °C for 30 hours, enabling a million-fold reduction of the bioburden [67].

There are a number of different methods to reduce the bioburden, but dry heat microbial reduction (DHMR) is currently the only approved full-system microbial reduction method [68]. However, for any subsystems incompatible with DHMR, alternative methods recently approved or currently under evaluation, such as Vapor-Phase Hydrogen Peroxide (VHP) [68], ethylene oxide, and gamma radiation and electron beams should be used. Also, passive sterilization through the high particle fluxes, encountered after launch to Europa, will further reduce the bioburden.

Due to the comparably smaller size and the CubeSat-inherited concept, faster assembly and easier accessibility to individual components will be enabled. This will mitigate several of the problems experienced by larger conventional spacecraft. For instance, less resources and allocated time are expected to be required for assembly, and the entire spacecraft can be treated for microbial reduction in a relatively small high-grade cleanroom facility, making sterilization both easier to reach while also better maintaining total system-level sterilization. Furthermore, the spacecraft should be smoothly designed with minimal external attachments, minimizing specific bioburden areas that are difficult to clean. Also, by using high-temperature and radiation tolerant components, a harsher sterilization method is possible. In case of an accidental impact with Europa, the impacting energy released due to the spacecrafts 5 km/s hypervelocity relative to the moon is expected to kill remaining organisms carried on the spacecraft. The typical requirement for a low probability of collision may be waived for these hypervelocity impact cases [69].

VII CONCLUSIONS

The *Plume Chaser – Plume Maker* mission concept presents a relatively low-cost architecture to explore the dwarf planet Ceres, investigate the content of water vapor detected around its surface and characterize possible biologically important molecules. Results are applicable to open questions regarding the formation of the asteroid belt, origin of volatiles and the future habitability of Ceres. While *Dawn* will characterize surface features on Ceres in 2015, *Plume Maker* and *Plume Chaser* would be the first spacecraft to fly through and sample emanated plumes, and create an impact cavity that facilitates study of subsurface chemistry and interior composition. While the primary goals of this mission are scientific, secondary goals of opportunity include the validation of critical technologies for use on a small-satellite platform, including CubeSat-based propulsion engines, miniaturized spectrometers and modular 3D-printed titanium propellant tanks. Once flight-tested the configuration may be applied to future small spacecraft missions to Europa, Enceladus or other bodies in the asteroid belt. Inclusive of launch and operations costs, the mission is Discovery Class in funding profile, and would secure a pathway for the future of low-cost, repeatable solar system exploration.

VIII ACKNOWLEDGEMENTS

This work was performed at the NASA Ames Mission Design Center, Mountain View, California. The authors acknowledge contributions by Tori Hoehler, Alfonso Davila, Eldar Noe, John Karcz, Andrew Gonzales, Larry Lemke, Hugo Sanchez, Anthony Genova, Brian Lewis and James Bell (Ames Research Center) and Benjamin Longmier and David Hash (University of Michigan). Financial support for Michael Nayak was provided by the NASA Ames Research Center / University of California Santa Cruz University Affiliated Research Center (UARC), Red Sky Research LLC and the National Defense Science and Engineering Graduate Fellowship (NDSEG).

IX REFERENCES

[1] Roth, L., Saur, J., Retherford, K. D., & Strobel, D. (2014). Transient Water Vapor at Europa's South Pole.Science. *Science* , pp. 171-174.

[2] Küppers, M., L. O'Rourke, B. Carry, D. Bockelée-Morvan, D. Teyssier, S. Lee, P. van Allmen, A. Marston, K. Crovisier, and T. Müller (2013), The water regime of dwarf planet (1) Ceres, *III Encuentro sobre Ciencias Planetarias y Explor. del Sist. Solar, Fac. Ciencias Geológicas*, 14–15.

[3] Küppers, M. et al. (2014), Localized sources of water vapour on the dwarf planet (1) Ceres, *Nature*, *505*(7484), 525–527.

[4] Li, J.-Y., L. A. McFadden, J. W. Parker, E. F. Young, S. A. Stern, P. C. Thomas, C. T. Russell, and M. V Sykes (2006), Photometric analysis of 1 Ceres and surface mapping from HST observations, *Icarus*, *182*(1), 143–160.

[5] Carry, B., C. Dumas, M. Fulchignoni, W. J. Merline, J. Berthier, D. Hestroffer, T. Fusco, and P. Tamblyn (2007), Near-infrared mapping and physical properties of the dwarf-planet Ceres, *arXiv Prepr. arXiv0711.1152*.

[6] McCord, T. B., and C. Sotin (2005), Ceres: Evolution and current state, *J. Geophys. Res. Planets*, *110*(E5).

[7] Briggs, F. H. (1973), Radio emission from Ceres, *Astrophys. J.*, *184*, 637–640.

[8] Castillo-Rogez, J. C., and T. B. McCord (2010), Ceres' evolution and present state constrained by shape data, *Icarus*, *205*(2), 443–459.

[9] Castillo-Rogez, J. C. (2011), Ceres–Neither a porous nor salty ball, *Icarus*, *215*(2), 599–602.

[10] Rivkin, A. S., E. L. Volquardsen, and B. E. Clark (2006), The surface composition of Ceres: Discovery of carbonates and iron-rich clays, *Icarus*, *185*(2), 563–567.

[11] Pizzarello, S., G. W. Cooper, and G. J. Flynn (2006), The nature and distribution of the organic material in carbonaceous chondrites and interplanetary dust particles, *Meteorites early Sol. Syst. II*, *1*, 625–651.

[12] Milliken, R. E., and A. S. Rivkin (2009), Brucite and carbonate assemblages from altered olivine-rich materials on Ceres, *Nat. Geosci.*, *2*(4), 258–261.

[13] Pappalardo, R. T. , M. J. S. Belton, H. H. Breneman, M. H. Carr, C. R. Chapman, G. C. Collins, T. Denk, S. Fagents, P. E. Geissler, B. Giese, R. Greeley, R. Greenberg, J. W. Head, P. Helfenstein, G. Hoppa, S. D. Kadel, K. P. Klaasen, J. E. Klemaszewski, K. Magee, A. S. McEwen, J. M. Moore, W. B. Moore, G. Neukum, C. B. Phillips, L. M. Prockter, G. Schubert, D. A. Senske, R. J. Sullivan, B. R. Tufts, E. P. Turtle, R. Wagner, and K. K. Williams, "Does Europa have a subsurface ocean? Evaluation of the geological evidence," J Geophys Res, vol. 104, no. 10, pp. 24015–24055, 1999.

[14] Chyba C. and C. Phillips, "Europa as an abode of life," Origins of Life and Evolution of Biospheres, vol. 32, pp. 47–68, 2002.

[15] Billings S.E. and S. A. Kattenhorn, "The great thickness debate: Ice shell thickness models for Europa and comparisons with estimates based on flexure at ridges," Icarus, vol. 177, no. 2, pp. 397–412, 2005.

[16] Hand K.P., R. W. Carlson, and C. F. Chyba, "Energy, Chemical Disequilibrium, and Geological Constraints on Europa," Astrobiology, vol. 7, no. 6, pp. 1006–1022, 2007.

[17] Schmidt, B.E., D. D. Blankenship, G. W. Patterson, and P. M. Schenk, "Active formation of 'chaos

terrain' over shallow subsurface water on Europa," Nature, vol. 479, no. 7374, pp. 502–505, 2011.

[18] Kattenhorn S. A., L. M. Prockter, "Evidence of subduction in the ice shell of Europa", Nature Geoscience, 2014.

[19] Roth Lorenz, Saur J., Retherford K.D., Strobel D.F., Feldman P.D., McGrath M.A., Nimmo F., Transient Water Vapor at Europa's South Pole, Science, 343, 6167, 171-174, 2013

[20] Chyba C., and C. Phillips, "Possible Ecosystems and the Search for Life on Europa," Proc. Natl. Acad. Sci. U.S.A., vol. 98, no. 3, pp. 801–804, 2001.

[21] National Research Council (2011), *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, DC.

[22] Russell, C. T., A. Coradini, U. Christensen, M. C. De Sanctis, W. C. Feldman, R. Jaumann, H. U. Keller, A. S. Konopliv, T. B. McCord, and L. A. McFadden (2004), Dawn: A journey in space and time, *Planet. Space Sci.*, *52*(5), 465–489.

[23] Denevi, B. W., D. T. Blewett, D. L. Buczkowski, F. Capaccioni, M. T. Capria, M. C. De Sanctis, W. B. Garry, R. W. Gaskell, L. Le Corre, and J.-Y. Li (2012), Pitted terrain on Vesta and implications for the presence of volatiles, *Science (80-.).*, *338*(6104), 246–249.

[24] McSween Jr, H. Y., D. W. Mittlefehldt, A. W. Beck, R. G. Mayne, and T. J. McCoy (2012), HED meteorites and their relationship to the geology of Vesta and the Dawn mission, in *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*, pp. 141–174, Springer.

[25] Bland, M. T. (2013), Predicted crater morphologies on Ceres: Probing internal structure and evolution, *Icarus*, *226*(1), 510–521.

[26] Rayman, M. D., and R. A. Mase (2010), The second year of Dawn mission operations: Mars gravity assist and onward to Vest, *Acta Astronaut.*, *67*(3), 483–488.

[27] Polanskey, C. A., S. P. Joy, C. A. Raymond, and M. D. Rayman (2014), Architecting the Dawn Ceres Science Plan, *Sp. Oper. Pasadena, CA.*

[28] Russell, C. T., C. A. Raymond, R. Jaumann, H. Y. McSween, M. C. Sanctis, A. Nathues, T. H. Prettyman, E. Ammannito, V. Reddy, and F. Preusker (2013), Dawn completes its mission at 4 Vesta, *Meteorit. Planet. Sci.*, *48*(11), 2076–2089.

[29] Rayman, M. D., and R. A. Mase (2014), Dawn′ s exploration of Vesta, *Acta Astronaut.*, *94*(1), 159–167.

[30] Rousselot, P., E. Jehin, J. Manfroid, O. Mousis, C. Dumas, B. Carry, U. Marboeuf, and J.-M. Zucconi (2011), A search for water vaporization on Ceres, *Astron. J.*, *142*(4), 125.

[31] Melosh, H. J. (1989), *Impact Cratering: A Geologic Process*, Oxford University Press.

[32] Colaprete, A., R. Elphic, J. Heldmann, and K. Ennico (2012), An Overview of the Lunar Crater Observation and Sensing Satellite (LCROSS), *Space Sci. Rev.*, *167*(1-4), 3–22, doi:10.1007/s11214-012-9880-6.

[33] Srama, R., and F. Postberg (2014), *Enceladus Icy Jets Analyzer – ENIJA Info Sheet.*

[34] Chester, R. (2000), *Marine Geochemistry*, 2nd ed., Blackwell Publishers, London, UK.

[35] Woffinden, D. C. (2004), On-Orbit Satellite Inspection: Navigation and Delta-V Analysis, 1–215 pp., Massachussetts Institute of Technology.

[36] Woffinden, D. C. (2008), Angles-Only Navigation for Autonomous Orbital Rendezvous, 1–320 pp., Utah State University.

[37] Woffinden, D. C., and D. K. Geller (2007), Navigating the Road to Autonomous Orbital Rendezvous, *J. Spacecr. Rockets*, *44*(4), 898–909, doi:10.2514/1.30734.

[38] GOMSpace (2013), GOMSpace NanoCam C1U spec sheet, Available from: http://gomspace.com/documents/GS-DS-NANOCAM-6.2.pdf (Accessed 29 October 2014).

[39] Maly, J., J. Goodding, G. Fuji, and C. Swaner (2013), ESPA Satellite Dispenser for ORBCOMM Generation 2

[40] Moog/CSA Engineering (2012), *ESPA Grande Adapters.*

[41] Kitts, C., J. Hines, E. Agasid, A. Ricco, B. Yost, K. Ronzano, and J. Puig-Suari (2006), The GeneSat-1 Microsatellite MissionA Challenge in Small Satellite Design

[42] Diaz-Aguado, M. F., S. Ghassemieh, C. Van Outryve, C. Beasley, and A. Schooley (2009), Small Class-D spacecraft thermal design, test and analysis-PharmaSat biological experiment, in *Aerospace conference, 2009 IEEE*, pp. 1–9, IEEE.

[43] Whorton, M., A. Heaton, R. Pinson, G. Laue, and C. Adams (2008), Nanosail-D: the first flight demonstration of solar sails for nanosatellites

[44] Minelli, G., A. Ricco, C. Beasley, J. Hines, E. Agasid, B. Yost, D. Squires, C. Friedericks, M. Piccini, and G. Defouw (2010), O/OREOS nanosatellite: A multi-payload technology demonstration

[45] Martinez, A., G. Cappuccio, and D. Tomko (2013), NASA Facts: SporeSat

[46] Sheehan, J. P., T. A. Collard, B. W. Longmier, and I. M. Goglio (2014), New Low-Power Plasma Thruster for Nanosatellites

[47] Kolosa, K. L. D., S. Spangelo, and J. Hudson (2014), Mission analysis for a micro rf ion thruster for cubesat orbital maneuvers, in *Joint Propulsion Conference, Cleveland, OH*

[48] Longmier, B. (2014), The CubeSat Ambipolar Thruster: Earth Escape in a 3U CubeSat, in *Interplanetary Small Satellite conference*, Jet Propulsion Laboratory, Pasadena, CA.

[49] Goodson, T. D., D. L. Gray, Y. Hahn, and F. Peralta (1998), Cassini maneuver experience: Launch and early cruise, in *AIAA Guidance, Navigation*, vol. 63.

[50] Sarani, S. (2010), Enceladus Plume Density Modeling and Reconstruction for Cassini Attitude Control System, in *SpaceOps 2010 Conference*.

[51] Blue Canyon Technologies (2013), Spacecraft Reaction Wheels, Available from: http://bluecanyontech.com/all_products/reaction-wheels

[52] Greenbaum, A., T. Brady, and C. J. Dennehy (2014), Finding the gaps in space GNC hardware, in *Aerospace Conference, 2014 IEEE*, pp. 1–15, IEEE.

[53] Mueller, J., J. Ziemer, R. Hofer, R. Wirz, and T. ODonnell (2008), A survey of micro-thrust propulsion options for microspacecraft and formation flying missions, in *5th Annual CubeSat Developers Workshop San Luis Obispo, CA.*

[54] Hruby, V. (2003), Review of electric propulsion activites in the US industry, *World, 80*, 90.

[55] Franquiz, F., P. Edwards, B. Udrea, and M. V Nayak (2014), Attitude Determination and Control System Design for a 6U CubeSat for Proximity Operations and Rendezvous, *AIAA Sp. 2014 Conf. Expo.*, 1–18, doi:10.2514/6.2014-4421.

[56] Babuscia, A., K.-M. Cheung, C. Lee, and T. Choi (2014), Communication and Coverage Analysis for a network of small satellites around Mars, in *Interplanetary Small Satellite conference*, Jet Propulsion Laboratory, Pasadena, CA.

[57] Abraham, D. S., and B. E. MacNeal (2014), Opportunistic MSPA: A Low Cost Downlink Alternative for Deep Space SmallSats, in *Interplanetary Small Satellite conference*, Jet Propulsion Laboratory, Pasadena, CA.

[58] Lluch, I., and A. Golkar (2014), Satellite-to-satellite coverage optimization approach for opportunistic inter-satellite links, in *Aerospace Conference, 2014 IEEE*, pp. 1–13, IEEE.

[59] Duncan, C., and A. Smith (2014), IRIS DSN Compatible Small Satellite Navigation & Communications Transponder, in *Interplanetary Small Satellite conference*, Jet Propulsion Laboratory, Pasadena, CA.

[60] Ravichandran, M., and J. Thanga (2014), Cubesat Based Inflatable Antennas and Structures for Inter-planetary Communciatin and Tracking, in *Interplanetary Small Satellite conference*, Jet Propulsion Laboratory, Pasadena, CA.

[61] SpaceX, n.d. *Launch Manifest.* [Online] Available at: www.spacex.com/missions [Accessed May 2014].

[62] NASA (2005), Planetary protection provisions for robotic extraterrestrial missions, in *NPR 8020.12 C*, pp. 1–380, National Aeronautics and Space Administration, Washington DC.

[63] Glasstone, S., and P. J. Dolan (1977), The effects of nuclear weapons, in *The effects of nuclear weapons*, US Department of Defense; US Department of Energy.

[64] Air Force Institute of Technology (1991), *Critical Technologies for National Defense*, AIAA.

[65] National Research Council (2000). *Preventing the Forward Contamination of Europa.*Washington D.C: National Academy Press.

[66] NASA. *Planetary Protection Provisions for Robotic Extraterrestrial Missions.* NPR 8020.12D.

[67] JPL (2011). *Assessment of Planetary Protection and Contamination Control Technologies for Future Planetary Science Missions.* Pasadena.

[68] Frick, A., Mogul, R., Stabekis, P., Conley, C. A., & Ehrenfreund, P. (n.d.). *Overview of Current Capabilities and Research and Technology Developments for Planetary Protection*.[Online] Available at: http://dx.doi.org/10.1016/j.asr.2014.02.016 [Accessed May 2014]

[69] Bernard, D. et. al. (2013). Europa planetary protection for Juno Jupiter Orbiter. *Advances in Space Research*, p. 547–568.